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**EFFECT OF STAY-IN-PLACE METAL
FORMS ON PERFORMANCE OF
CONCRETE BRIDGE DECKS**

Final Report

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UDOT RESEARCH & DEVELOPMENT REPORT ABSTRACT

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Abstract: <p>The objective of this research was to investigate the effect of stay-in-place metal forms (SIPMFs) on the performance of concrete bridge decks in Utah. The research program included 12 decks all located within the Interstate 215 corridor in the vicinity of Salt Lake City, Utah. Test methods included visual inspection, chain dragging, hammer sounding, Schmidt hammer testing, half-cell potential testing, and chloride concentration testing. The collected data were subjected to analysis of covariance (ANOCOVA) testing, with age and cover as covariates.</p> <p>Differences in crack width, Schmidt rebound number, half-cell potential, and chloride concentration at 2-in. depth between decks with and without SIPMFs were determined to be significant. Specifically, the decks with SIPMFs had a lower crack width, a higher compressive strength, a more active state of corrosion, and a higher chloride concentration at the time of testing, which may all be attributable to elevated moisture contents in decks with SIPMFs arising from the reduction in deck surface area from which moisture may evaporate. These data indicate that decks with SIPMFs are clearly more susceptible to reinforcement corrosion compared to decks without SIPMFs and may therefore exhibit greater magnitudes of damage with time. Given these research findings, engineers should carefully compare the short-term advantages against the potential long-term disadvantages associated with the use of SIPMFs for concrete bridge deck construction.</p>					
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TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	viii
CHAPTER 1 INTRODUCTION	1
1.1 Problem Statement	1
1.2 Scope	2
1.3 Outline of Report	2
CHAPTER 2 STAY-IN-PLACE METAL FORMS	3
2.1 Overview	3
2.2 Use of Stay-in-Place Metal Forms	3
2.3 Performance of Stay-in-Place Metal Forms	5
2.4 Summary	6
CHAPTER 3 EXPERIMENTAL METHODOLOGY	9
3.1 Testing Plan	9
3.2 Visual Inspection	13
3.3 Chain Dragging and Hammer Sounding	14
3.4 Schmidt Hammer Testing	15
3.5 Half-Cell Potential Testing	15
3.6 Chloride Concentration Testing	18
3.7 Summary	20
CHAPTER 4 TEST RESULTS	21
4.1 Overview	21
4.2 Distress Survey	21
4.3 Schmidt Hammer Testing	33
4.4 Half-Cell Potential Testing	34
4.5 Chloride Concentration Testing	35
4.6 Statistical Analyses	35
4.7 Summary	41
CHAPTER 5 CONCLUSION	43
5.1 Summary	43

5.2 Findings	44
5.3 Recommendations	44
REFERENCES	47

LIST OF TABLES

TABLE 3.1	Summary of Bridge Data for Decks with SIPMFs	10
TABLE 3.2	Summary of Bridge Data for Decks without SIPMFs	11
TABLE 3.3	List of Random Numbers	13
TABLE 3.4	Crack Severity Categories.....	14
TABLE 4.1	Distress Survey Results for Decks with SIPMFs.....	31
TABLE 4.2	Distress Survey Results for Decks without SIPMFs.....	32
TABLE 4.3	Schmidt Hammer Data.....	33
TABLE 4.4	Half-Cell Potential Data.....	34
TABLE 4.5	Chloride Concentration Data for Decks with SIPMFs.....	36
TABLE 4.6	Chloride Concentration Data for Decks without SIPMFs	37
TABLE 4.7	Summary of Chloride Concentration Data.....	38
TABLE 4.8	Results of Statistical Analyses	39

LIST OF FIGURES

FIGURE 2.1 Bottom View of an SIPMF.....	4
FIGURE 3.1 Bridge Deck Locations.....	12
FIGURE 3.2 Example Selection of Test Areas for 100-ft Deck.....	13
FIGURE 3.3 Testing Layout.....	13
FIGURE 3.4 Use of Cover Meter to Locate Rebar.....	16
FIGURE 3.5 Connection of Half-Cell Potential Meter to Rebar.....	17
FIGURE 3.6 Half-Cell Potential Measurement.....	17
FIGURE 3.7 Hole Dimensions for Chloride Concentration Sampling.....	18
FIGURE 3.8 Example of a Drilled Hole.....	19
FIGURE 3.9 Collection of Pulverized Concrete Samples.....	19
FIGURE 4.1 Distress Survey for Deck C-460.....	22
FIGURE 4.2 Distress Survey for Deck C-688.....	23
FIGURE 4.3 Distress Survey for Deck C-698.....	24
FIGURE 4.4 Distress Survey for Deck C-699.....	25
FIGURE 4.5 Distress Survey for Deck C-726.....	26
FIGURE 4.6 Distress Survey for Deck C-760.....	27
FIGURE 4.7 Distress Survey for Deck F-500.....	28
FIGURE 4.8 Distress Survey for Deck F-504.....	29
FIGURE 4.9 Distress Survey for Deck F-506.....	30

CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Although the use of stay-in-place metal forms (SIPMFs) in concrete bridge deck construction has increased since the 1970s (*1*), many differing opinions exist about the effect of SIPMFs on bridge deck durability. Some state departments of transportation (DOTs) use SIPMFs frequently and are pleased with their performance. However, other DOTs only allow SIPMFs in special situations, and still other DOTs forbid their use altogether, fearing that the presence of SIPMFs may accelerate reinforcement corrosion and compromise long-term deck durability (*1*). Indeed, among 39 responses received in a national questionnaire survey of state DOTs, 13 indicated that SIPMFs are not allowed in concrete bridge deck construction (*1*).

The Utah Department of Transportation (UDOT) has constructed several bridge decks using SIPMFs in the past, but the current policy prohibits their use. Contractors have been pressuring UDOT engineers to continue allowing bridge deck construction using SIPMFs. The disparity of opinions regarding the effect of SIPMFs on deck durability led UDOT to commission this research to investigate the effect of SIPMFs on concrete bridge deck performance.

Past research on SIPMFs has investigated the state-of-the-practice concerning deck construction using SIPMFs, determined the effect of SIPMFs on moisture content in connection with freeze-thaw deterioration, and compared the overall performance of bridge decks with and without SIPMFs by visual inspection, compressive strength testing, and ultrasonic testing (*1, 2*). However, the influence of SIPMFs on chloride concentration, which is a key factor in the corrosion of deck reinforcement, remains largely unaddressed in the literature.

Therefore, the specific objectives of this research were to investigate the effect of SIPMFs on the corrosion of steel reinforcement by evaluating chloride concentration together with half-cell potential, Schmidt rebound number, and deck distress. Half-cell potential testing was included in this study to evaluate the corrosion activity of the reinforcing steel, Schmidt hammer testing was utilized to estimate concrete strength, and deck distress surveys were conducted to quantify existing deck distress.

1.2 SCOPE

The research program included 12 concrete bridge decks located within the Interstate 215 (I-215) corridor in the vicinity of Salt Lake City, Utah. Six of these bridge decks were constructed using SIPMFs, and six were constructed using conventional formwork. All of the bridge decks were constructed between 1984 and 1989 using epoxy-coated rebar. The bridge decks were analyzed using visual inspection, chain dragging, hammer sounding, Schmidt hammer testing, half-cell potential testing, and chloride-concentration testing.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. In Chapter 2, the results of a literature review addressing the use and performance of SIPMFs are provided. Descriptions of the experimental plan and the field and laboratory testing procedures are given in Chapter 3. Test results and statistical analyses are explained in Chapter 4 together with a discussion of the research findings. In Chapter 5, summaries of the procedures, research findings, and recommendations are presented.

CHAPTER 2

STAY-IN-PLACE METAL FORMS

2.1 OVERVIEW

The following sections present a comprehensive literature review of SIPMFs, including descriptions of the state-of-the-practice concerning the use of SIPMFs and issues associated with the performance of concrete bridge decks constructed using SIPMFs.

2.2 USE OF STAY-IN-PLACE METAL FORMS

In concrete bridge deck construction, three main types of formwork are available. The most common is temporary formwork consisting of plywood and lumber that is removed after the concrete has cured sufficiently. A second type of formwork consists of permanent, precast, prestressed concrete deck panels that are integrated into the overall deck thickness. As shown in Figure 2.1, the third type is permanent formwork made of thin, corrugated sheets of galvanized steel, which are referred to as SIPMFs (*1*).

SIPMFs are practical in a number of applications. In 1972, the Federal Highway Administration issued an instructional memorandum endorsing the use of permanent forms in high-traffic areas, over deep ravines, and in other hazardous locations (*1, 3*). In these situations, eliminating the need to remove concrete forms decreases the exposure of construction workers to elevated levels of risk.

SIPMFs also accelerate the construction process because they are prefabricated, easy to install, and do not require removal (*4*). For example, rehabilitation of a high-volume bridge outside of Columbus, Ohio, would have required 18 months to finish using conventional methods but was finished in just 47 days due in part to the use of



FIGURE 2.1 Bottom view of an SIPMF.

SIPMFs; as a result, the project received the Associated General Contractors of America AON Build America Merit Award in 2004 (5). Since the expense of formwork usually constitutes 35 to 60 percent of total bridge construction costs (3), the use of SIPMFs can also result in substantial cost savings associated with reduced labor requirements, construction time, and traffic control.

Despite the advantages of permanent forms, several disadvantages warrant consideration. First, the presence of SIPMFs may exacerbate deck deterioration by causing higher moisture and salt contents within the deck (1, 4). Second, the metal forms may corrode over time, causing unsightliness and possible danger to the traveling public. Lastly, the presence of SIPMFs prevents bridge inspectors from viewing the underside of the bridge deck. These three reasons have been cited as the primary limiting factors for the use of SIPMFs in the United States (1, 6).

The results of a questionnaire survey conducted of all state DOTs in 2004 indicate that 26 of the 39 respondents allow the use of SIPMFs (1). The majority of the DOT participants stated that the use of SIPMFs was not linked to any deck deterioration,

although corrosion of the SIPMFs was reported by 12 DOTs (1). Of the 13 states that do not allow the use of SIPMFs, 12 were concerned primarily with the inability to inspect the underside of the deck (1). Only two were in the southern United States, suggesting that the acceptance of SIPMFs for deck construction in southern states is higher than in northern states characterized by colder winters and the accompanying use of deicing salts for roadway maintenance.

2.3 PERFORMANCE OF STAY-IN-PLACE METAL FORMS

Since the introduction of SIPMFs to the concrete bridge deck construction industry, a few studies have been published evaluating their effect on bridge deck performance. Research has shown that decks with SIPMFs are characterized by higher moisture contents than those with conventional formwork; the increase in moisture results from the reduction in exposed deck surface area from which water may evaporate (7). Higher moisture, in turn, increases the probability of frost damage to bridge decks in cold climates, as the 9 percent expansion of water upon freezing can lead to the development of tensile stresses within the concrete (2, 7, 8). Higher moisture contents also increase the rate at which chlorides diffuse into the concrete; higher levels of saturation are generally associated with greater continuity within the pore water system, which increases the diffusivity of chloride ions in the concrete matrix (9, 10).

While durability of the concrete itself is a primary factor governing overall bridge deck performance, the corrosion of deck reinforcement is considered to be the most severe and frequent form of deterioration in reinforced concrete (4, 11). Rust formed through the corrosion process is 200 to 600 percent greater in volume than its parent materials (12), which causes substantial tensile stresses in the concrete. Cracking occurs when the tensile stress exceeds the tensile strength of the concrete. The formation of rust also causes the steel reinforcement to suffer a reduction in cross-sectional area and a corresponding decrease in load-bearing capacity that can lead to further increases in tensile stress within the concrete and additional cracking (12).

The principal causes of reinforcement corrosion are elevated water contents and chloride concentrations within the deck (13); the destruction of the passive oxide layer on steel reinforcement by chlorides is especially well documented in the literature (14).

One author states that once the steel is depassivated the service life of the deck has ended due to uncertainties in the rate of corrosion (13).

Although concerns regarding deterioration of concrete bridge decks with SIPMFs have been frequently cited (15), only a limited amount of field data evaluating the effects of SIPMFs on bridge deck performance has been collected, and those data appear inconclusive. For example, the author of one study states that decks constructed using steel forms “are no more prone to freeze-thaw deterioration than wood-formed decks” (2, p. 20). In another study, core samples extracted from five decks with and five decks without SIPMFs were visually inspected for corrosion of rebar and were assigned a score from zero to three, with zero indicating the absence of corrosion (1). Although not computed by the authors of the publication describing the study, the mean corrosion index of decks with SIPMFs was 2.04, which was 17 percent higher than the mean corrosion index of 1.70 calculated for the decks without SIPMFs. Possible reasons for the greater corrosion index of decks with SIPMFs include elevated water and chloride concentrations within the deck, as mentioned previously, but those data were not collected in that study. No studies investigating the effects of SIPMFs on chloride concentrations were identified in the literature.

2.4 SUMMARY

The literature describes several advantages and disadvantages associated with the use of SIPMFs. The advantages include reduction of the overall cost and time associated with bridge deck construction and decreasing exposure of workers to elevated levels of risk. The principle disadvantages include possible acceleration of deck deterioration and inability of bridge engineers to view the underside of the bridge deck. Although concerns regarding deterioration of concrete bridge decks with SIPMFs have been frequently cited, only a limited amount of field data evaluating the effects of SIPMFs on bridge deck performance has been collected, and those data appear inconclusive. The variety of opinions about the performance of concrete bridge decks with SIPMFs is reflected in the results of a national questionnaire survey sent to all state DOTs to investigate the state-of-the-practice concerning bridge deck construction using SIPMFs.

Among 39 responses received, 13 indicated that SIPMFs are not allowed in concrete bridge deck construction.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 TESTING PLAN

UDOT personnel selected six decks with SIPMFs and six decks without SIPMFs for evaluation in this research. Because all 12 decks were located within the I-215 corridor in the vicinity of Salt Lake City, Utah, they were subject to similar traffic loading, climatic conditions, and maintenance treatments, including applications of deicing salts during winter months. Although different contractors were probably involved with construction of the individual decks, the same concrete mixture design specification was utilized by UDOT in all cases. At the time of testing, the bridges ranged in age from 16 to 21 years as shown in Tables 3.1 and 3.2, which provide specific information about decks with SIPMFs and decks without SIPMFs, respectively. A map showing the bridge locations is given in Figure 3.1, in which the black stars represent decks with SIPMFs and the white stars represent decks without SIPMFs.

On each bridge deck, six randomly distributed 6-ft by 6-ft test locations were evaluated within the single lane closed for testing. Thus, 36 test locations per deck type were evaluated. The number of test locations required per deck was determined using statistics from the spatial variation associated with chloride concentration test results obtained in previous work (16). Randomizing the test locations within the lane was necessary to ensure that every possible test location had an equal chance of being selected.

For randomization of the test locations, the length of the deck was first measured. This length in feet was then multiplied by two and divided by six to compute the number of available test areas on the deck. Finally, the total number of available test areas was multiplied by six predetermined random numbers between zero and one to facilitate

TABLE 3.1 Summary of Bridge Data for Decks with SIPMFs

Bridge ID	Year of Deck Construction	Deck Age at Time of Testing	Direction of Travel	Actual Direction Tested	Mile Post	Location	Facility	Featured Intersection	Polymer Overlay	Date Testing Performed	SIPMF
C-460	1988	17	NB & SB	NB	21.4	850 S & 2000 W	I-215	Indiana Ave & Railroad	No	21-May	Yes
C-688	1987	18	NB & SB	NB	21.9	500 S & 2000 W	I-215	I-215 & 500 S	No	14-May	Yes
C-698	1987	18	NB	NB	21.8	500 S & 2000 W	Ramp from I-215 NB to I-80 EB	500 S & Railroad	No	21-May	Yes
C-699	1987	18	NB	NB	21.8	N of 500 S at 2000 W	Ramp from I-215 NB to I-80	I-215 & Railroad	No	21-May	Yes
C-759	1989	16	EB & WB	WB	6.5	0.2 mi SW of Knudson Cnr Int	I-215	I-215 & Holladay Blvd	Yes	4-Jun	Yes
C-760	1989	16	WB	WB	6.5	0.2 mi SW of Knudson Cnr Int	On-ramp to I-215 WB	I-215 & Holladay Blvd	No	4-Jun	Yes

TABLE 3.2 Summary of Bridge Data for Decks without SIPMFs

Bridge ID	Year of Deck Construction	Deck Age at Time of Testing (yrs)	Direction of Travel	Actual Direction Tested	Mile Post	Location	Facility	Featured Intersection	Polymer Overlay	Date Testing Performed	SIPMF
C-726	1984	21	NB & SB	NB	9.5	6550 S & 900 E	SR-71 (900 E)	I-215 & 900 E	No	16-Jul	No
C-736	1987	18	WB	WB	7.7	6600 S & 2000 E	On-ramp to I-215 WB	I-215 & SR-152	Yes	30-Jul	No
C-752	1988	17	NB & SB	NB	20.6	W of Redwood Rd at California Ave	I-215	I-215 & California Ave	Yes	14-May	No
F-500	1984	21	NB & SB	NB	23.3	700 N & 2000 W	I-215	I-215 & 700 N	No	16-Jul	No
F-504	1984	21	NB & SB	SB	8.0	6650 S & 1300 E	1300 East	I-215 & 1300 E	No	4-Jun	No
F-506	1985	20	NB & SB	NB	8.1	2300 E & 6450 S	2300 South	I-215 & 2300 S	No	16-Jul	No

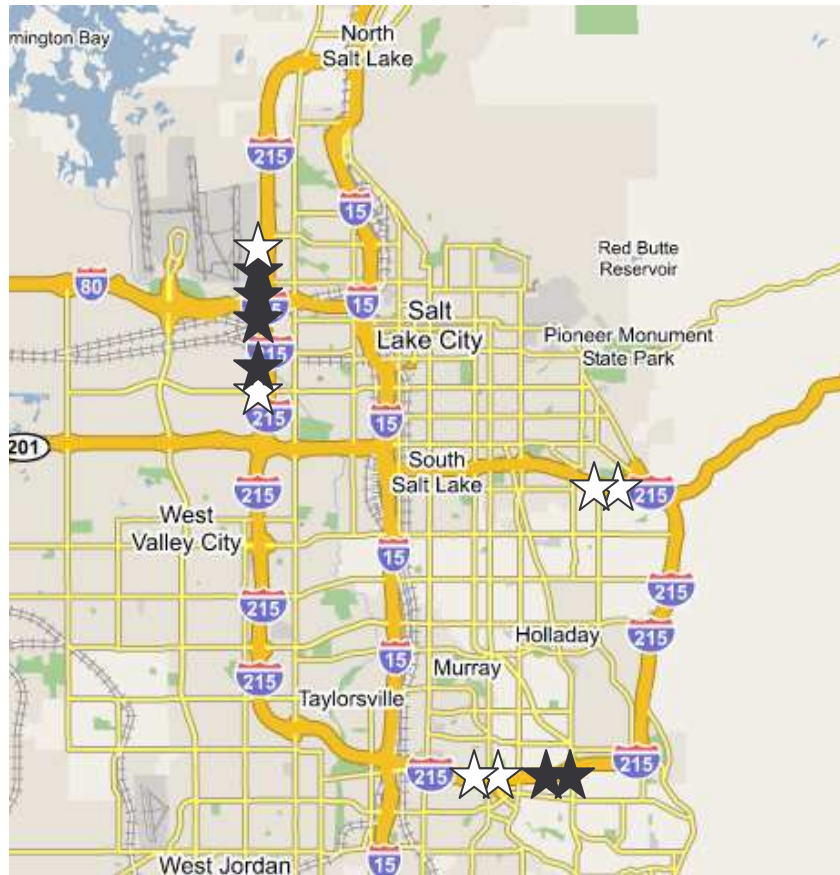


FIGURE 3.1 Bridge deck locations.

selection of six test locations. The same random numbers, which are shown in Table 3.3, were used for all bridge decks. Figure 3.2 displays the relative locations of the randomly selected test areas on a hypothetical deck 100 ft in length. The test areas are labeled with bold numbering.

Several tests were performed at each test location, including visual inspection, chain dragging, hammer sounding, Schmidt hammer testing, half-cell potential testing, and chloride concentration testing. While the entire area of each test location was inspected for distress, Figure 3.3 depicts the specific locations at which the other tests were performed. The following sections discuss each of the test procedures.

TABLE 3.3 List of Random Numbers

Random Numbers
0.1493
0.2956
0.5765
0.7241
0.8450
0.9573

1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34

FIGURE 3.2 Example selection of test areas for 100-ft deck.

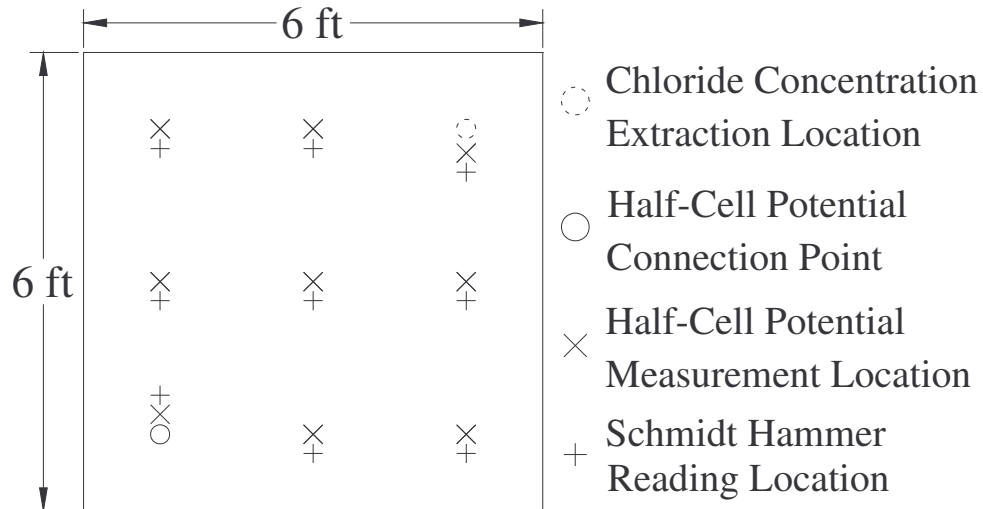


FIGURE 3.3 Testing layout.

3.2 VISUAL INSPECTION

The primary purpose of visual inspection was to document the presence of any cracks or potholes within each test location. The width, length, and orientation of each

crack and the location and size of each pothole were recorded; a crack width comparator card was used to measure crack widths. The average crack width, crack severity, crack density, number of potholes, average pothole size, and pothole density were then computed from the collected data. Crack severities were categorized from average crack widths using Table 3.4, and crack density was calculated by dividing the total length of cracking in feet by the total area of the test section in square yards. Pothole density was calculated by dividing the total area in square feet of all potholes in the test area by the total area of the test section in square yards.

As indicated in Tables 3.1 and 3.2, two of the bridge decks without SIPMFs and one deck with SIPMFs had polymer overlays. Because the presence of the surface treatments prohibited view of any cracking in the concrete deck, visual inspection was limited to potholes on these decks.

TABLE 3.4 Crack Severity Categories (17)

Category	Crack Width (in.)
Hairline	<0.004
Narrow	0.004 to 0.01
Medium	0.01 to 0.03
Wide	>0.03

3.3 CHAIN DRAGGING AND HAMMER SOUNDING

Chain dragging and hammer sounding were performed to locate subsurface delaminations within each test location. In the chain-dragging test, a steel chain was dragged back and forth within the test area, and the operator listened for changes in the acoustical response of the deck. In the hammer-sounding test, the surface of the deck within the test area was tapped with a standard carpentry hammer to evaluate the deck integrity. In both cases, intact concrete was characterized by a clear ringing sound, while delaminated concrete produced a dull, hollow sound (18, 19).

When delaminations were identified, the estimated diameter of the defect was recorded. The number of delaminations, average delamination size, and delamination density were then determined, with the latter two being reported in square feet per square

yard. Although delaminations on decks with polymer overlays may result from actual delaminations in the concrete, which was of primary interest in this research, they may also result from separations of the surface treatment from the underlying concrete surface. Because the type of delamination could not be readily determined, all delaminations were recorded during field testing.

3.4 SCHMIDT HAMMER TESTING

The Schmidt hammer test provided a means of estimating the compressive strength of bare concrete decks and was used to measure the Schmidt rebound number at nine locations within each test area as shown in Figure 3.3. The test was not performed on the three decks surfaced with polymer overlays, however, because the surface of the concrete deck could not be exposed for evaluation. An average Schmidt rebound number was computed for each test location to estimate the concrete compressive strength. Higher compressive strengths generally correspond to greater resistance of the concrete to damage.

3.5 HALF-CELL POTENTIAL TESTING

Half-cell potential testing was performed to assess the corrosion state of the reinforcing steel within each test area on each deck. Because the rebar was epoxy-coated and electrical continuity between test locations was therefore not assured, separate connections to the rebar were established at each test location as depicted in Figure 3.3. Since half-cell potential measurements are only valid for the individual rebar to which the meter is attached when electrical continuity is not present, this protocol ensured that valid readings would be obtained in every test location; this process of establishing discrete connection points on the epoxy-coated rebar and then conducting the half-cell potential survey in the near vicinity of the connection point has also been utilized by other researchers (20).

As illustrated in Figure 3.4, a cover meter was used to establish the location of the rebar within each test area. Then, a hammer drill equipped with a 1-in.-diameter bit was used to expose the rebar at a single location to facilitate an electrical connection to the reinforcement. The drilling process stripped the rebar of its epoxy coating and

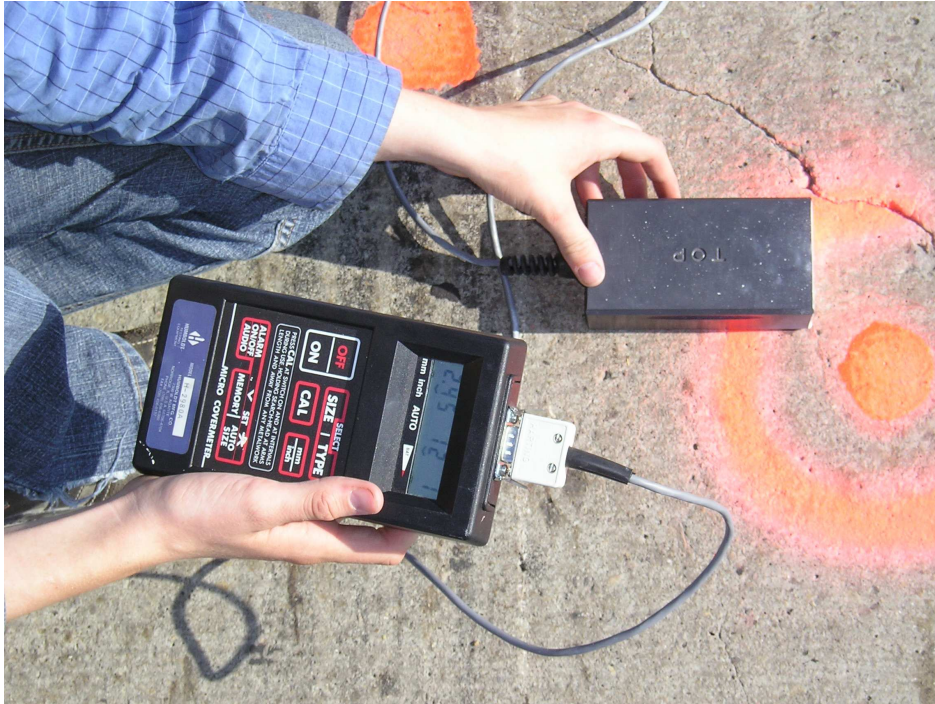


FIGURE 3.4 Use of cover meter to locate rebar.

allowed an electrical lead from the half-cell potential meter to be directly connected to bright metal on the rebar as shown in Figure 3.5. Half-cell potential measurements were then obtained at the nine locations shown in Figure 3.3 using a copper-copper sulfate reference electrode (CSE), which was coupled to the concrete deck surface through a moistened sponge as depicted in Figure 3.6 (14). An average half-cell potential value was computed for each test location for assessment of the reinforcement corrosion activity. The depth of concrete cover over the rebar was also measured after the reinforcement was exposed.

According to American Society for Testing and Materials (ASTM) C 876, Standard Test Method for Half-Cell Potential of Uncoated Reinforcing Steel in Concrete, potential measurements more negative than -0.35 V measured with a CSE indicate a probability larger than 90 percent that corrosion of the steel is occurring. Potential measurements more positive than -0.20 V indicate a probability larger than 90 percent that corrosion is not occurring, and potential measurements between -0.20 and -0.35 V indicate that corrosion in that area is uncertain.

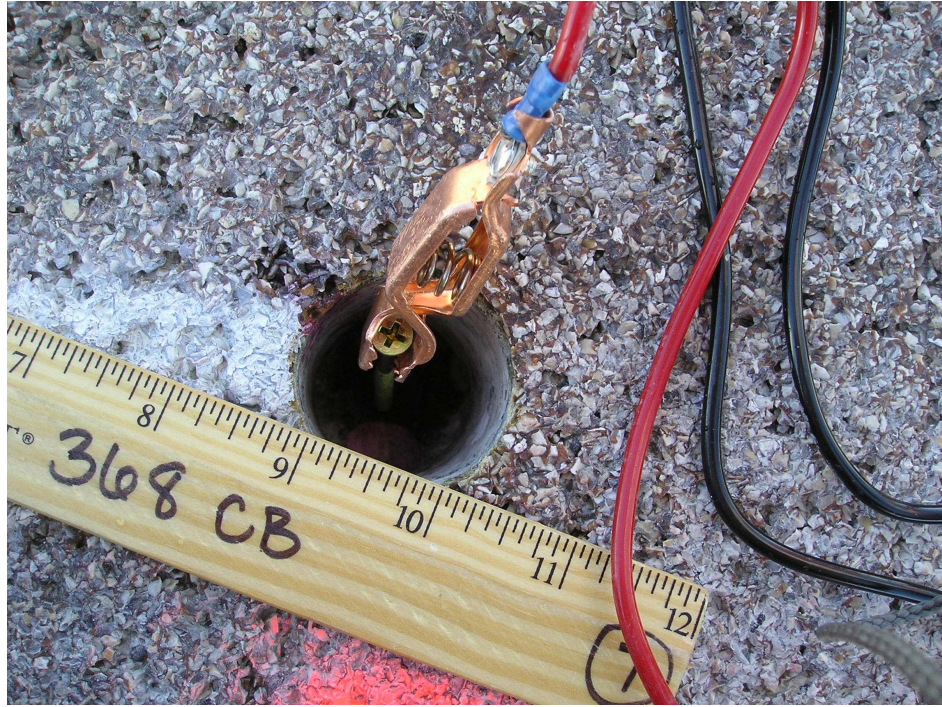


FIGURE 3.5 Connection of half-cell potential meter to rebar.

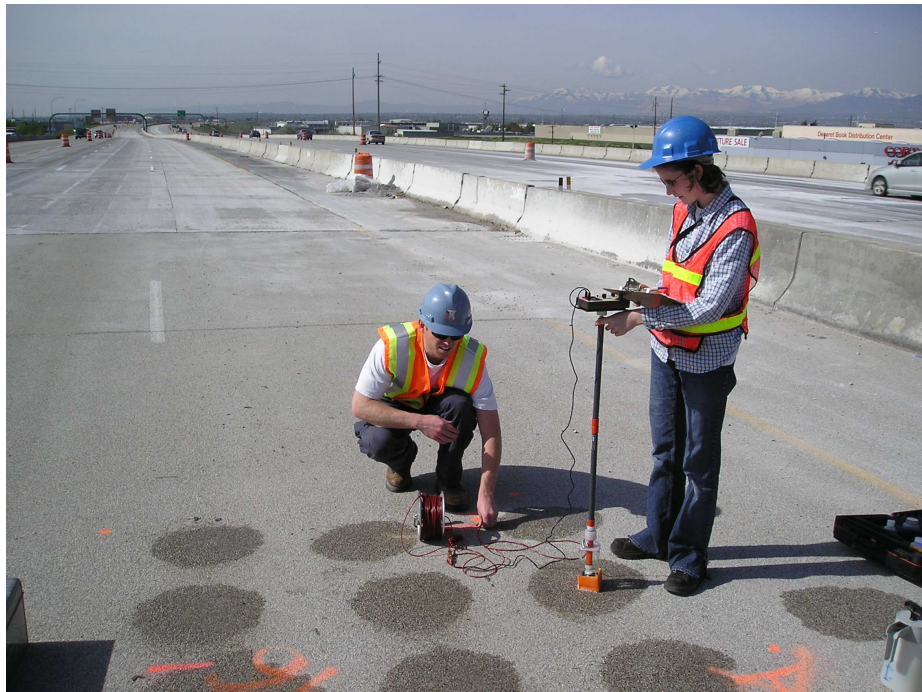


FIGURE 3.6 Half-cell potential measurement.

3.6 CHLORIDE CONCENTRATION TESTING

Chloride extractions were performed in one location within each test area as shown in Figure 3.3. Each extraction was accomplished in seven or eight approximately 1-in. lifts; on decks without SIPMFs, only seven lifts were removed to avoid drilling through the bottom of the deck. Four different hammer drill bits ranging in size from 1.5 in. to 0.75 in. in diameter were used. The drill bit diameter was decreased 0.25 in. after every two lifts to minimize contamination of deeper samples by reducing the probability that near-surface concrete would be inadvertently scraped during the drilling process. A schematic showing the sequential reductions in bit diameter with increasing depth is presented in Figure 3.7, and a picture of a typical hole resulting from this practice is shown in Figure 3.8.

After each lift was drilled, the pulverized concrete powder was manually removed from the test hole and placed into a plastic sample bag, as shown in Figure 3.9. The hole and drill bit were then cleaned using compressed air, the depth of the hole was measured using a digital micrometer, and the next lift was drilled.

Upon completion of the field testing, the pulverized concrete samples were transported to the Brigham Young University (BYU) Highway Materials Laboratory for chloride extractions following ASTM C 1218, Standard Test Method for Water

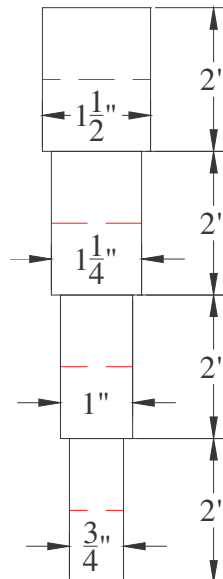


FIGURE 3.7 Hole dimensions for chloride concentration sampling.



FIGURE 3.8 Example of a drilled hole.



FIGURE 3.9 Collection of pulverized concrete samples.

Soluble Chloride in Mortar and Concrete (15). The requirement for the sample to pass through a No. 50 (0.0018-in.) sieve was satisfied by using a hammer drill for sample extraction. In the test, 0.35 oz of each sample was boiled in water for 5 minutes and then allowed to cool for 24 hours. After cooling, the solution was filtered and treated with equal amounts of nitric acid and hydrogen peroxide. The treated solution was then heated just to the boiling point and again allowed to cool for 24 hours. The chloride concentration of the solution was then measured using a laboratory chloride-ion-selective probe and converted from grams of chloride per milliliter to pounds of chloride per cubic yard of concrete based on an assumed concrete density of 145 lb/yd³.

To facilitate analysis of chloride concentration profiles, the midpoint of each depth interval was also computed, and chloride concentrations at 1-in. depth intervals were then determined for each test location by interpolation. Because chloride concentrations at the level of the steel reinforcement are of greatest concern with respect to corrosion of rebar, chloride concentrations of the decks with and without SIPMFs were expressly compared at a depth of 2 in., which was the target cover thickness for all of the decks according to UDOT specifications in place at the time the decks were constructed. Average chloride concentrations at 1-in. depth intervals were also computed for decks with and without SIPMFs to enable comparison of the overall chloride concentration profiles.

3.7 SUMMARY

In order to assess possible differences in deck performance between decks with SIPMFs and those without SIPMFs, BYU research personnel evaluated six bridge decks of each deck type. Because all 12 decks were located within the I-215 corridor in the vicinity of Salt Lake City, Utah, they were subject to similar traffic loading, climatic conditions, and maintenance treatments, including applications of deicing salts during winter months. Six test areas on each deck were randomly selected, and visual inspection, chain dragging, hammer sounding, Schmidt hammer testing, half-cell potential testing, and chloride concentration testing were performed within each test location.

CHAPTER 4

TEST RESULTS

4.1 OVERVIEW

The results of visual inspection, chain dragging, hammer sounding, Schmidt hammer testing, half-cell potential testing, and chloride concentration testing are presented in the following sections. General observations and statistical analyses are also described.

4.2 DISTRESS SURVEY

The distress survey forms completed in the field are replicated in Figures 4.1 to 4.9, excluding the decks with polymer overlays. Each figure contains all six areas per deck and documents the presence of cracks, delaminations, and potholes. The crack widths in inches are written next to each crack, and locations of delaminations and potholes are marked with “D” and “P,” respectively. On the decks with overlays, cracks in the concrete were masked by the overlay material, and no potholes or delaminations were identified.

The results of the visual inspections are given in Tables 4.1 and 4.2 and include the average crack width, crack severity, crack density, number of delaminations, delamination size, delamination density, number of potholes, and pothole density. Hyphens appear as entries in instances where the data could not be calculated. For example, hyphens are given as several entries for decks C-736, C-752, and C-759 due to the presence of polymer overlays.

The average crack width for decks without SIPMFs was 41 percent greater than that of decks with SIPMFs. Similarly, decks without SIPMFs had a higher crack density by 25 percent and had more potholes than decks with SIPMFs; in fact, the only deck

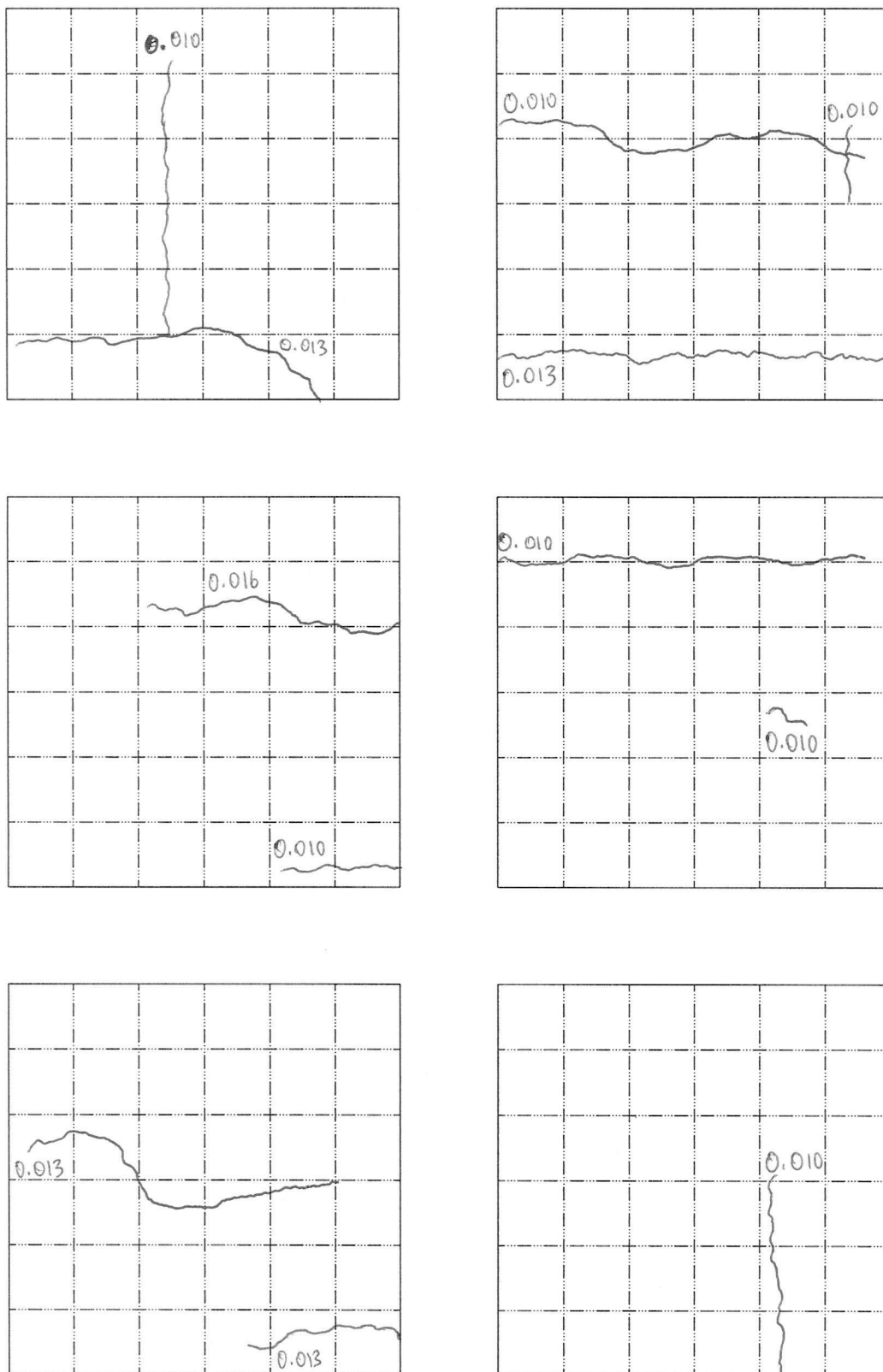


FIGURE 4.1 Distress survey for deck C-460.

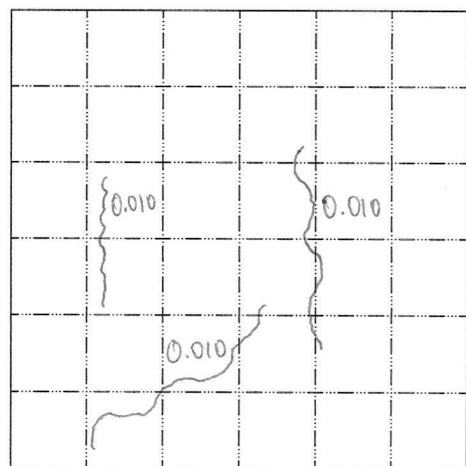
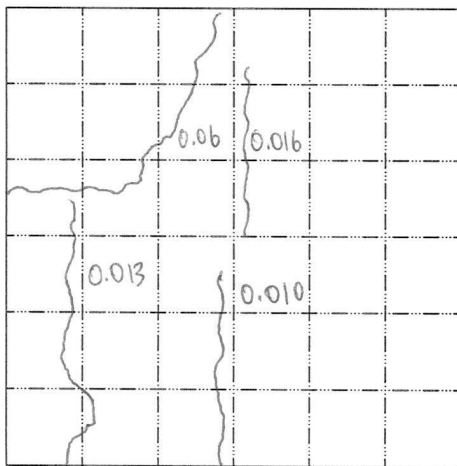
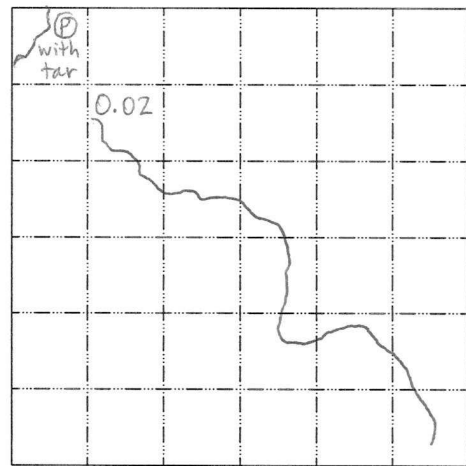
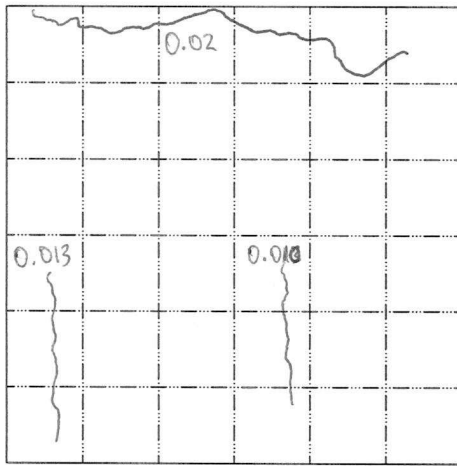
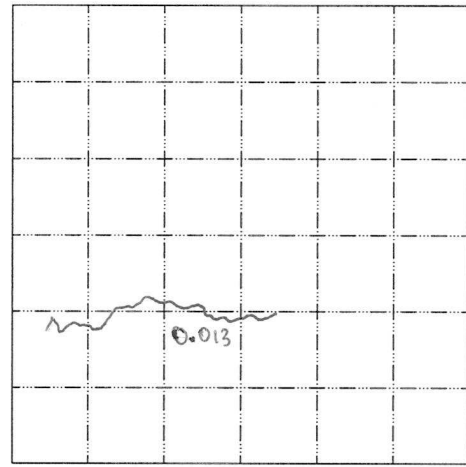
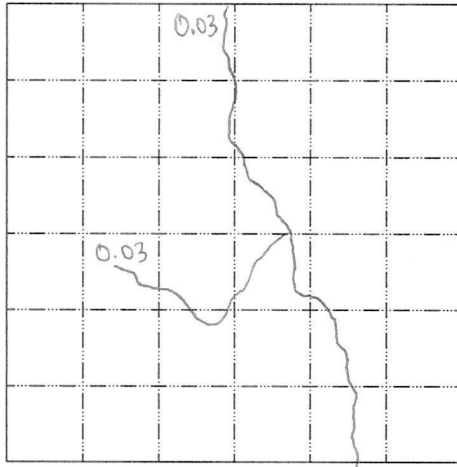


FIGURE 4.2 Distress survey for deck C-688.

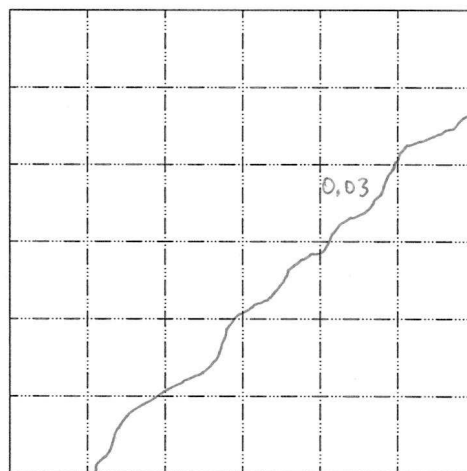
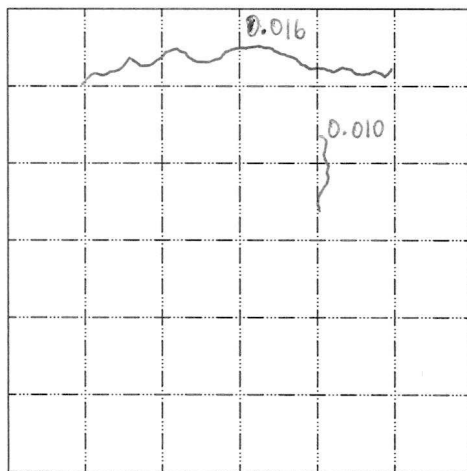
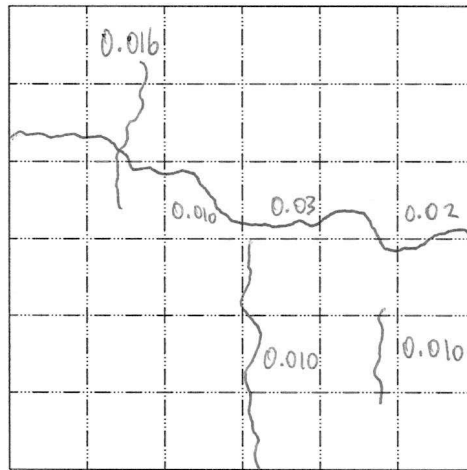
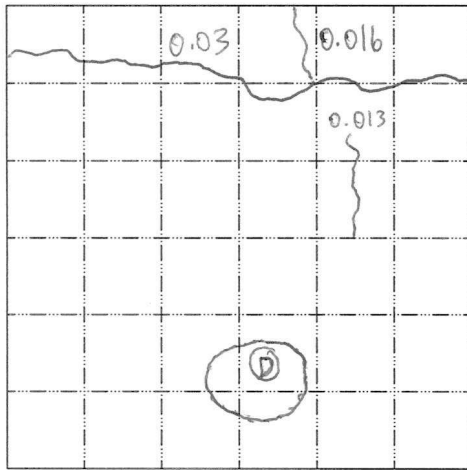
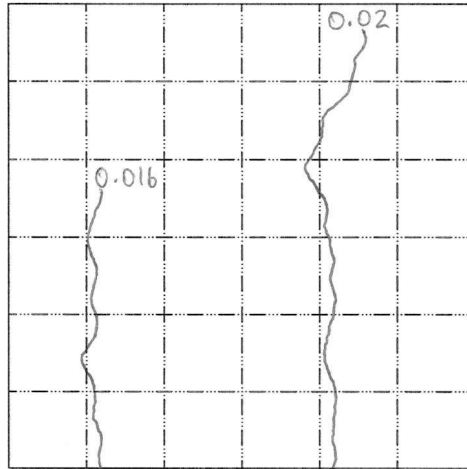
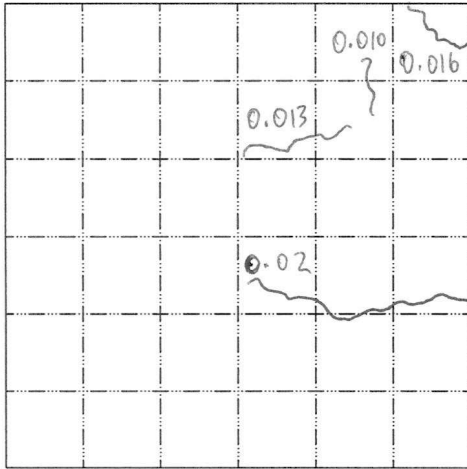


FIGURE 4.3 Distress survey for deck C-698.

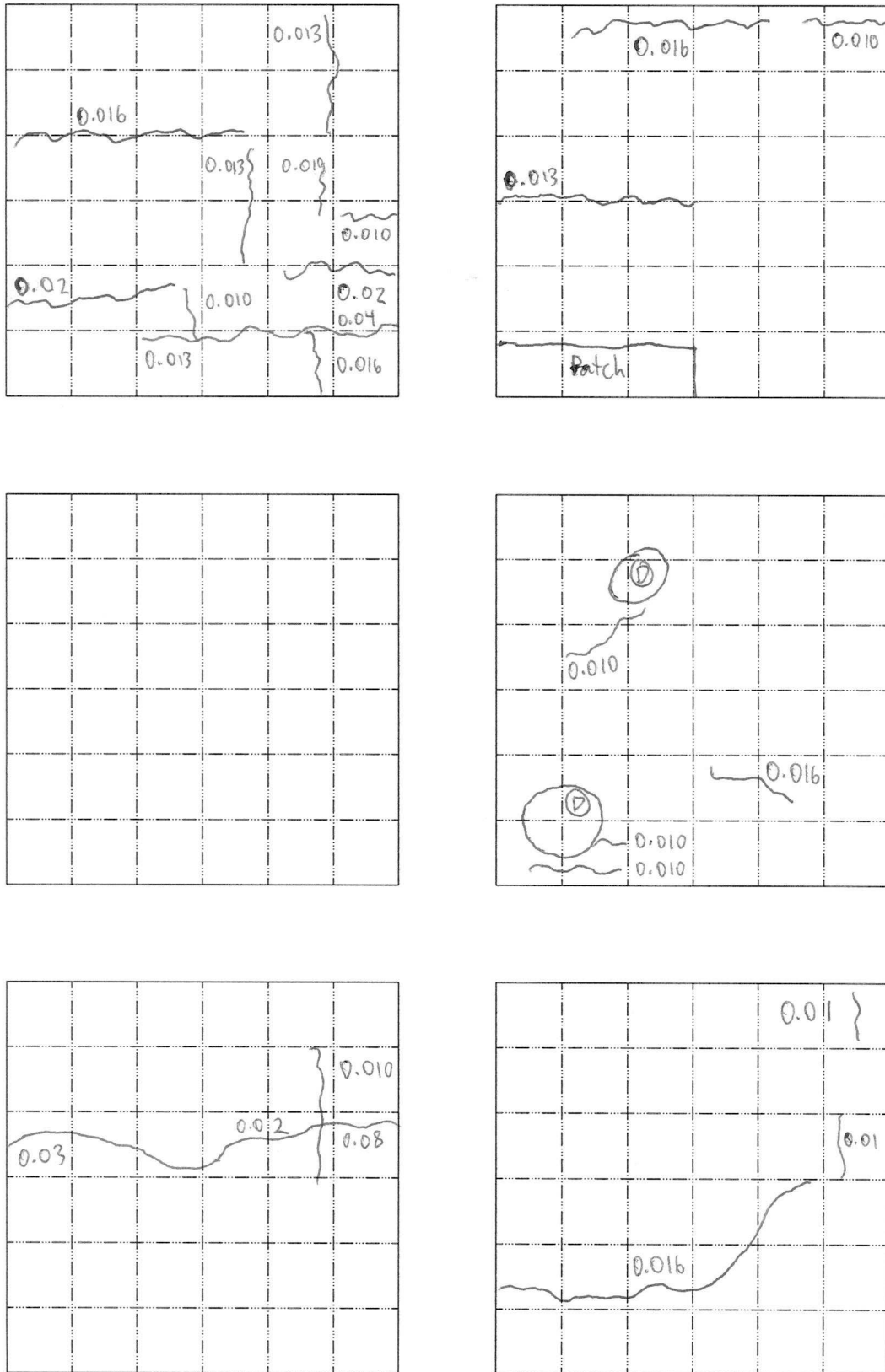


FIGURE 4.4 Distress survey for deck C-699.

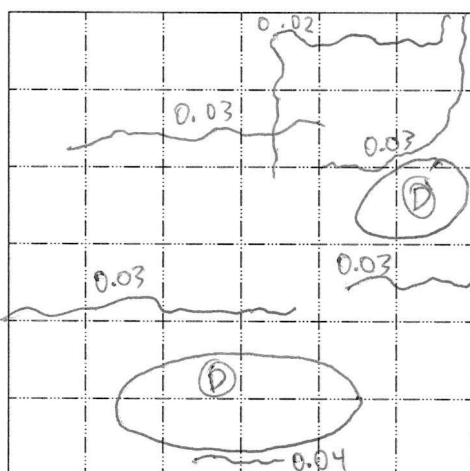
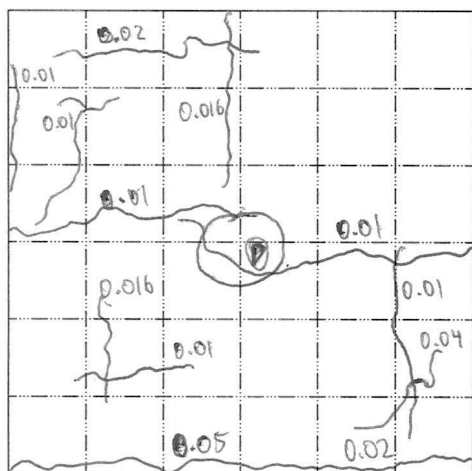
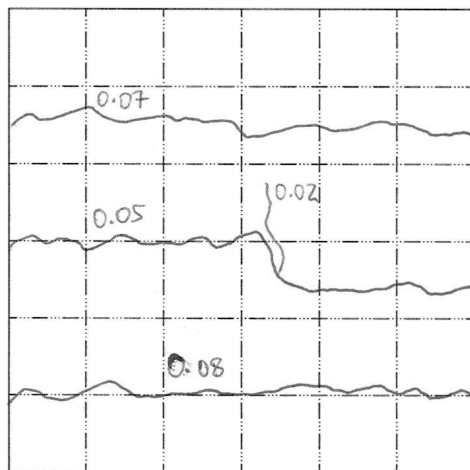
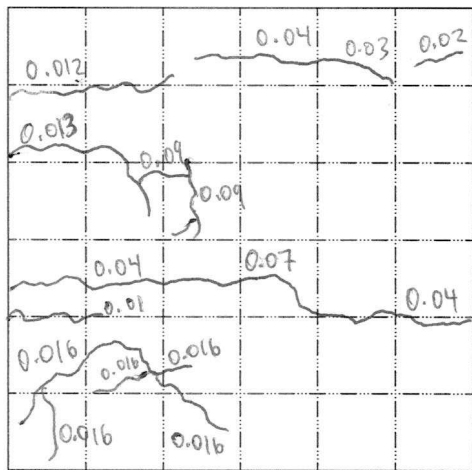
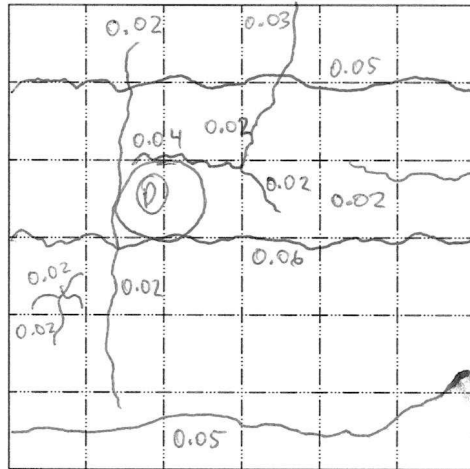
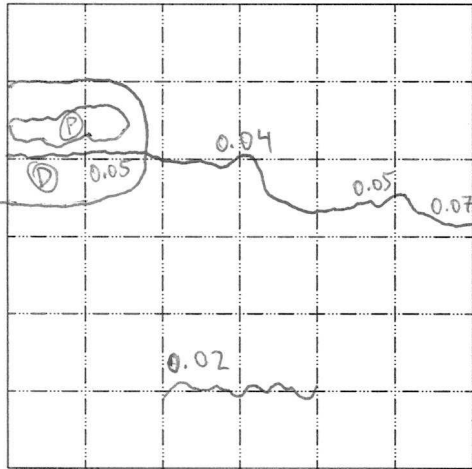


FIGURE 4.5 Distress survey for deck C-726.

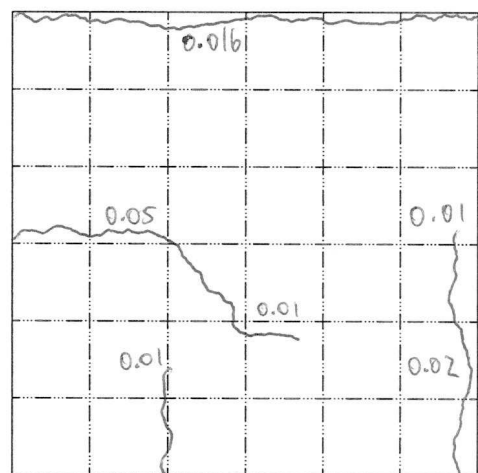
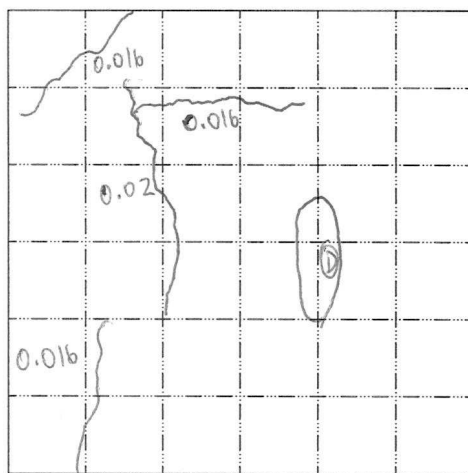
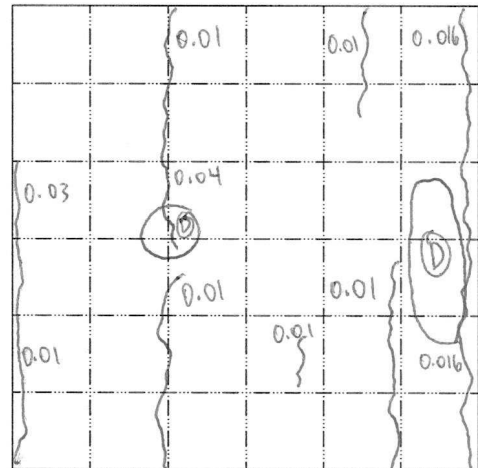
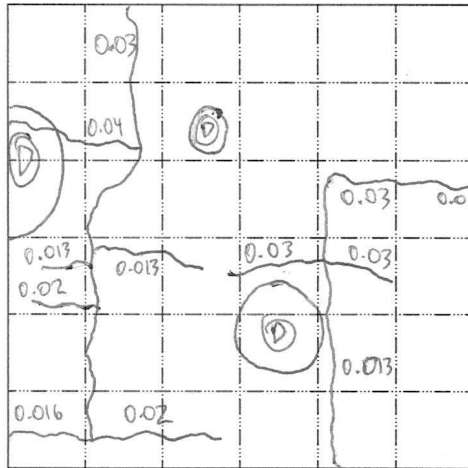
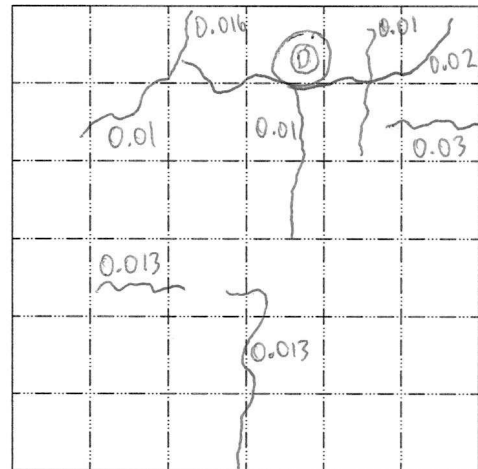
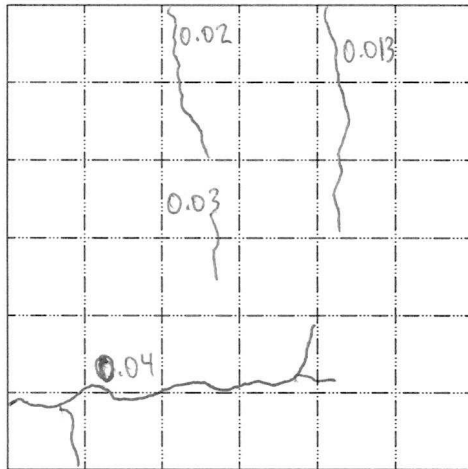


FIGURE 4.6 Distress survey for deck C-760.

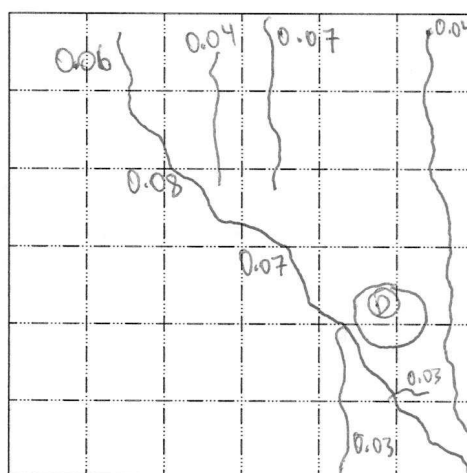
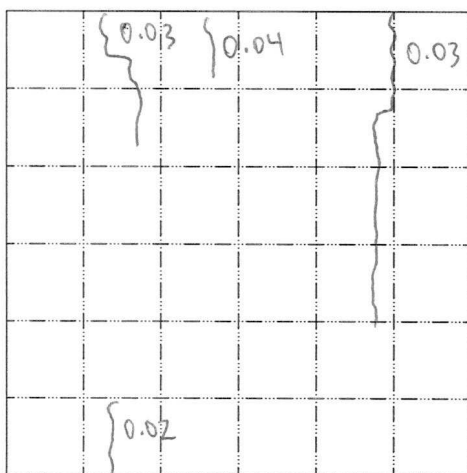
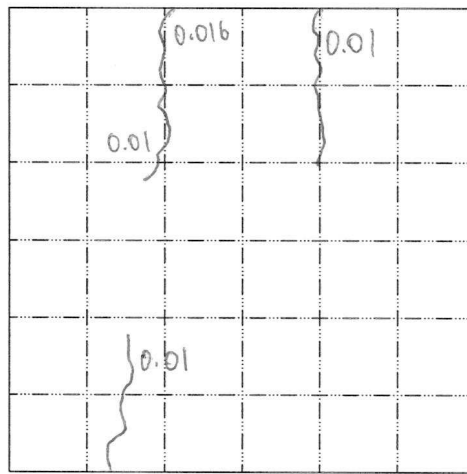
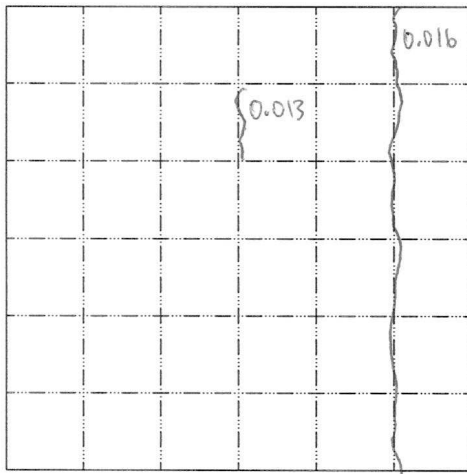
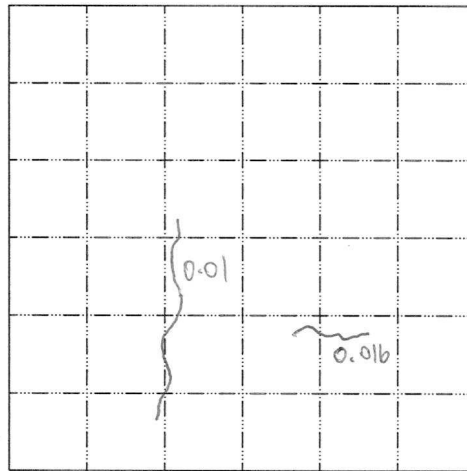
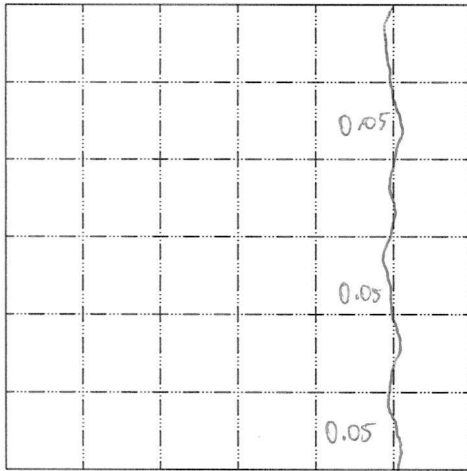


FIGURE 4.7 Distress survey for deck F-500.

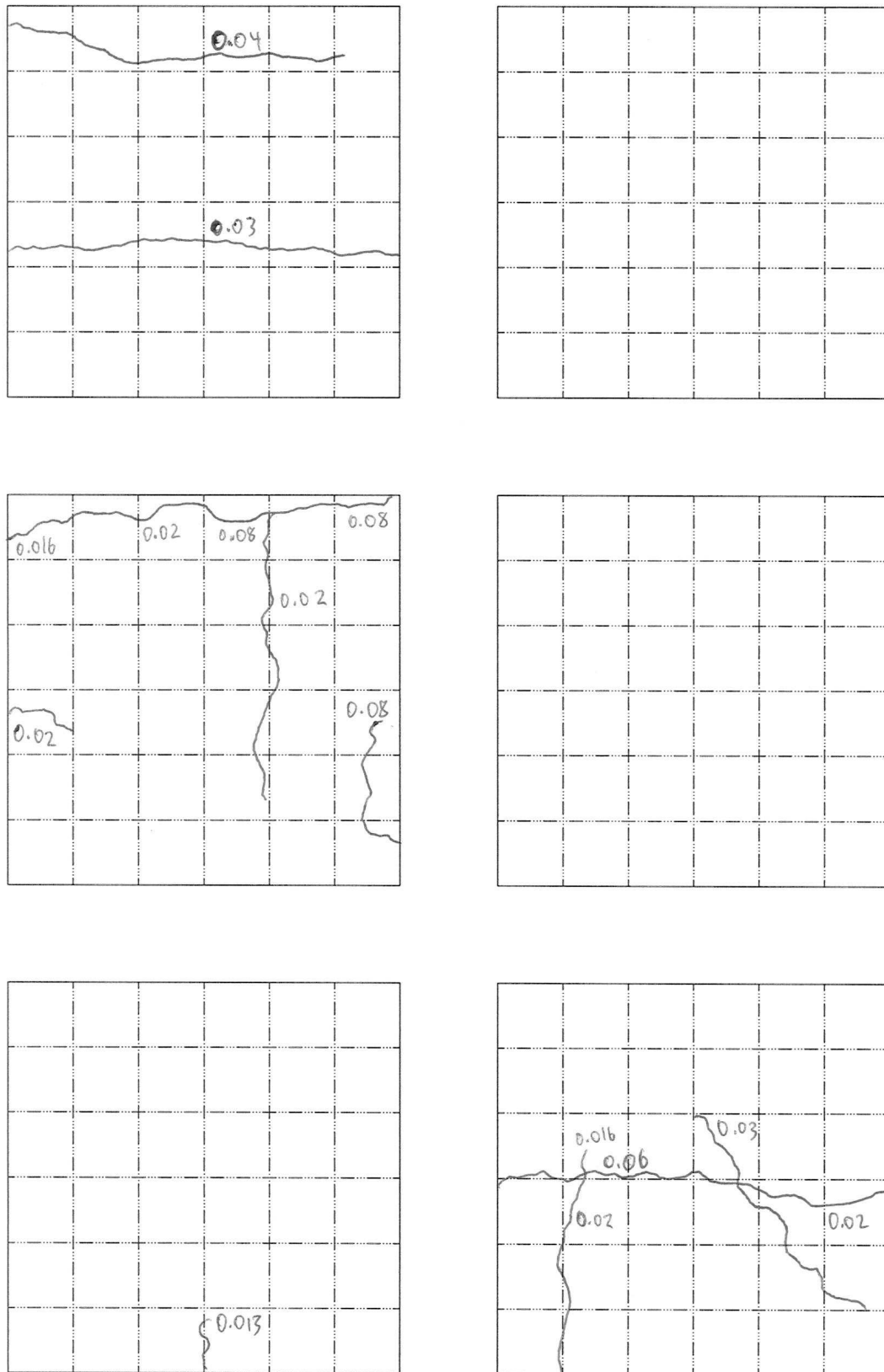


FIGURE 4.8 Distress survey for deck F-504.

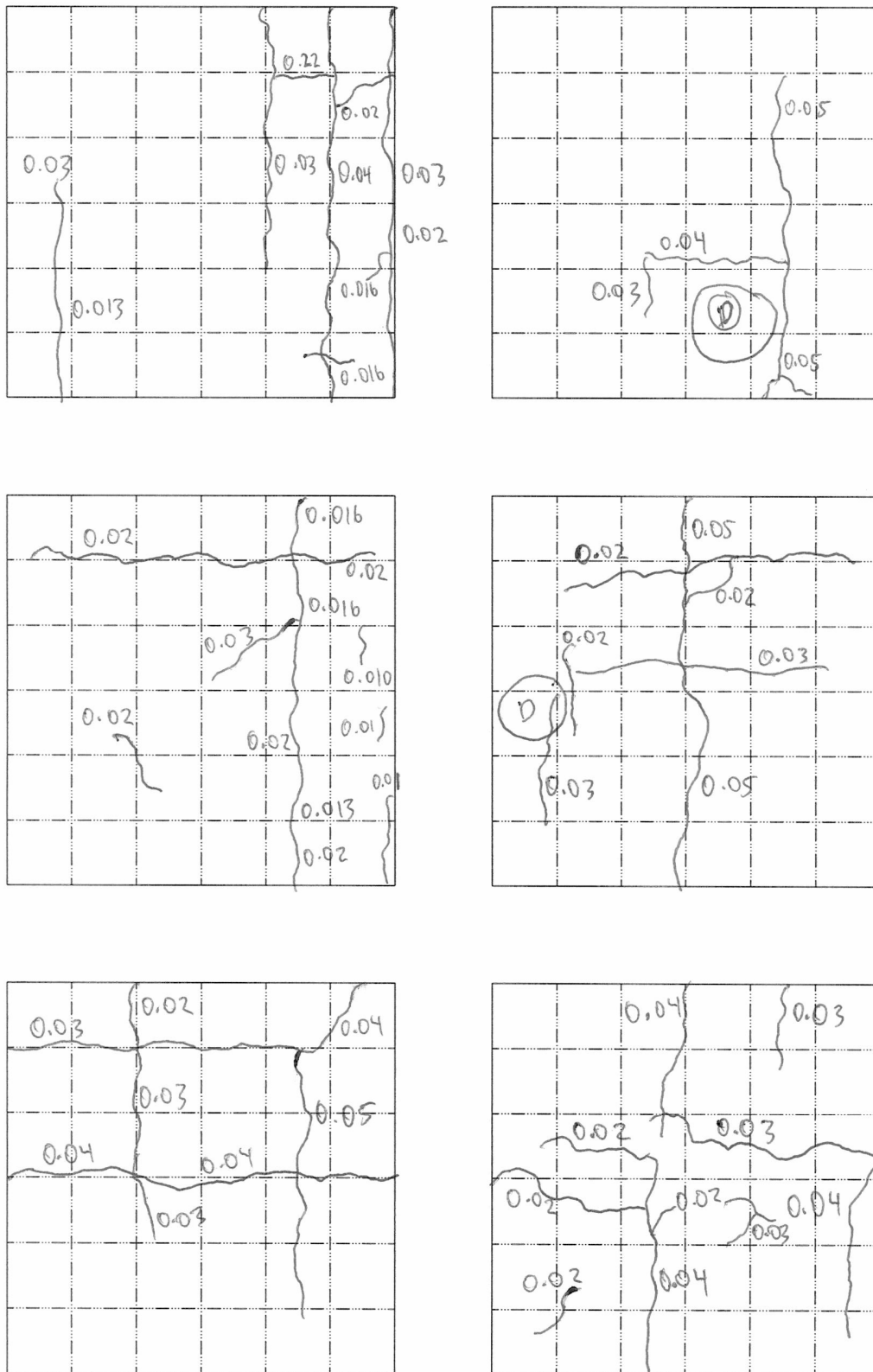


FIGURE 4.9 Distress survey for deck F-506.

TABLE 4.1 Distress Survey Results for Decks with SIPMFs

Deck ID	Test Area	Crack Width (in.)	Crack Severity	Crack Density (ft/yd ²)	Number of Delaminations	Delamination Size (ft ²)	Delamination Density (ft ² /yd ²)	Number of Potholes	Pothole Size (ft ²)	Pothole Density (ft ² /yd ²)
C-460	1	0.020	Medium	2.3	0	-	0.00	0	-	0.00
	2	0.011	Medium	3.3	0	-	0.00	0	-	0.00
	3	0.013	Medium	1.4	1	0.7	0.17	0	-	0.00
	4	0.010	Medium	1.6	0	-	0.00	0	-	0.00
	5	0.013	Medium	2.1	0	-	0.00	0	-	0.00
	6	0.010	Medium	0.8	0	-	0.00	0	-	0.00
C-688	1	0.030	Wide	2.4	0	-	0.00	0	-	0.00
	2	0.013	Medium	0.8	0	-	0.00	0	-	0.00
	3	0.014	Medium	2.3	0	-	0.00	0	-	0.00
	4	0.020	Medium	1.9	0	-	0.00	0	-	0.00
	5	0.019	Medium	3.3	0	-	0.00	0	-	0.00
	6	0.029	Medium	2.0	0	-	0.00	0	-	0.00
C-698	1	0.015	Medium	1.6	0	-	0.00	0	-	0.00
	2	0.018	Medium	2.6	0	-	0.00	0	-	0.00
	3	0.020	Medium	2.3	1	1.0	0.25	0	-	0.00
	4	0.014	Medium	3.2	0	-	0.00	0	-	0.00
	5	0.013	Medium	1.3	0	-	0.00	0	-	0.00
	6	0.030	Wide	1.8	0	-	0.00	0	-	0.00
C-699	1	0.018	Medium	5.5	0	-	0.00	0	-	0.00
	2	0.013	Medium	1.9	1	1.0	0.25	0	-	0.00
	3	0.000	-	0.0	0	-	0.00	0	-	0.00
	4	0.012	Medium	1.3	2	0.8	0.42	0	-	0.00
	5	0.027	Medium	2.2	0	-	0.00	0	-	0.00
	6	0.012	Medium	1.7	0	-	0.00	0	-	0.00
C-759	1	-	-	-	0	-	0.00	0	-	0.00
	2	-	-	-	0	-	0.00	0	-	0.00
	3	-	-	-	0	-	0.00	0	-	0.00
	4	-	-	-	0	-	0.00	0	-	0.00
	5	-	-	-	0	-	0.00	0	-	0.00
	6	-	-	-	0	-	0.00	0	-	0.00
C-760	1	0.026	Medium	2.8	0	-	0.00	0	-	0.00
	2	0.015	Medium	4.0	1	0.7	0.17	0	-	0.00
	3	0.022	Medium	5.8	3	0.9	0.67	0	-	0.00
	4	0.017	Medium	5.3	1	0.7	0.17	0	-	0.00
	5	0.017	Medium	2.3	1	1.1	0.28	0	-	0.00
	6	0.018	Medium	3.9	0	-	0.00	0	-	0.00
Average		0.018	Medium	2.58	0.33	0.89	0.07	0.00	-	0.00
Std. Dev.		0.007	-	1.36	0.67	0.16	0.15	0.00	-	0.00

TABLE 4.2 Distress Survey Results for Decks without SIPMFs

Deck ID	Test Area	Crack Width (in.)	Crack Severity	Crack Density (ft/yd ²)	Number of Delaminations	Delamination Size (ft ²)	Delamination Density (ft ² /yd ²)	Number of Potholes	Pothole Size (ft ²)	Pothole Density (ft ² /yd ²)
C-726	1	0.036	Wide	2.1	0	-	0.00	1	2.0	0.50
	2	0.034	Wide	8.2	1	1.0	0.25	0	-	0.00
	3	0.021	Medium	5.5	0	-	0.00	0	-	0.00
	4	0.050	Wide	5.0	0	-	0.00	0	-	0.00
	5	0.021	Medium	6.0	0	-	0.00	1	1.0	0.25
	6	0.029	Medium	4.6	2	2.3	0.56	0	-	0.00
C-736	1	-	-	-	0	-	0.00	0	-	0.00
	2	-	-	-	0	-	0.00	0	-	0.00
	3	-	-	-	0	-	0.00	0	-	0.00
	4	-	-	-	0	-	0.00	0	-	0.00
	5	-	-	-	0	-	0.00	0	-	0.00
	6	-	-	-	0	-	0.00	0	-	0.00
C-752	1	-	-	-	0	-	0.00	0	-	0.00
	2	-	-	-	0	-	0.00	0	-	0.00
	3	-	-	-	0	-	0.00	0	-	0.00
	4	-	-	-	0	-	0.00	0	-	0.00
	5	-	-	-	0	-	0.00	0	-	0.00
	6	-	-	-	0	-	0.00	0	-	0.00
F-500	1	0.050	Wide	1.5	0	-	0.00	0	-	0.00
	2	0.013	Medium	0.9	0	-	0.00	0	-	0.00
	3	0.015	Medium	1.8	0	-	0.00	0	-	0.00
	4	0.011	Medium	1.5	0	-	0.00	0	-	0.00
	5	0.030	Wide	2.3	0	-	0.00	0	-	0.00
	6	0.048	Wide	4.7	1	1.0	0.25	0	-	0.00
F-504	1	0.035	Wide	2.9	0	-	0.00	0	-	0.00
	2	0.000	-	0.0	0	-	0.00	0	-	0.00
	3	0.000	-	0.0	0	-	0.00	0	-	0.00
	4	0.000	-	0.0	0	-	0.00	0	-	0.00
	5	0.013	Medium	0.3	0	-	0.00	0	-	0.00
	6	0.028	Medium	3.5	0	-	0.00	0	-	0.00
F-506	1	0.026	Medium	5.8	0	-	0.00	0	-	0.00
	2	0.038	Wide	2.9	1	1.0	0.25	0	-	0.00
	3	0.017	Medium	4.3	0	-	0.00	0	-	0.00
	4	0.028	Medium	4.9	1	1.0	0.25	0	-	0.00
	5	0.037	Wide	5.7	0	-	0.00	0	-	0.00
	6	0.029	Medium	2.9	0	-	0.00	0	-	0.00
Average		0.025	Medium	3.22	0.17	1.25	0.04	0.06	1.50	0.02
Std. Dev.		0.015	-	2.26	0.45	0.56	0.12	0.23	0.71	0.09

that had potholes was a deck without SIPMFs. However, the delamination density for bridge decks with SIPMFs was 71 percent greater than that of decks without SIPMFs.

4.3 SCHMIDT HAMMER TESTING

Table 4.3 shows the results of the Schmidt hammer testing. Data are not provided for the three decks with polymer overlays since tests on bare concrete could not be conducted. The average Schmidt rebound numbers for decks with SIPMFs are higher than those for decks without SIPMFs by 4 points. This difference in rebound numbers is practically significant and suggests that the compressive strength of decks with SIPMFs is 1,400 psi greater than that of decks without SIPMFs.

TABLE 4.3 Schmidt Hammer Data

Deck	Test Area	With SIPMFs	Without SIPMFs
		Schmidt Rebound Number	Schmidt Rebound Number
1	1	41	40
	2	37	39
	3	38	37
	4	41	37
	5	42	37
	6	39	28
2	1	42	-
	2	41	-
	3	41	-
	4	40	-
	5	41	-
	6	43	-
3	1	37	-
	2	36	-
	3	37	-
	4	38	-
	5	36	-
	6	36	-
4	1	38	20
	2	39	33
	3	39	39
	4	40	-
	5	39	-
	6	38	-
5	1	-	38
	2	-	29
	3	-	38
	4	-	31
	5	-	26
	6	-	35
6	1	37	34
	2	36	34
	3	40	35
	4	38	38
	5	34	40
	6	39	40
Average		39	35
Std. Dev.		2	5

4.4 HALF-CELL POTENTIAL TESTING

The half-cell potential measurements obtained in this research are shown in Table 4.4. Although half-cell potentials were recorded in nine different areas within each test location, only the average of those nine values is shown in the table. The decks with SIPMFs have a value 0.123 lower than that of the decks without SIPMFs, indicating that a more active state of corrosion exists, on average, on the decks with SIPMFs. Specifically, over 58 percent of the test locations on decks with SIPMFs showed an active state of corrosion, whereas only 36 percent of the test locations on decks without SIPMFs showed an active state of corrosion.

TABLE 4.4 Half-Cell Potential Data

Deck	Test Area	With SIPMFs		Without SIPMFs	
		Half-Cell Potential (V)	Corrosion Activity	Half-Cell Potential (V)	Corrosion Activity
1	1	-0.347	Uncertain	-0.413	Active
	2	-0.337	Uncertain	-0.418	Active
	3	-0.450	Active	-0.497	Active
	4	-0.368	Active	-0.391	Active
	5	-0.235	Uncertain	-0.358	Active
	6	-0.322	Uncertain	-0.438	Active
2	1	-0.402	Active	-0.116	Inactive
	2	-0.394	Active	-0.166	Inactive
	3	-0.356	Active	-0.245	Uncertain
	4	-0.636	Active	-0.321	Uncertain
	5	-0.440	Active	-0.383	Active
	6	-0.446	Active	-0.223	Uncertain
3	1	-0.550	Active	-0.413	Active
	2	-0.581	Active	-0.273	Uncertain
	3	-0.279	Uncertain	-0.273	Uncertain
	4	-0.472	Active	-0.425	Active
	5	-0.481	Active	-0.188	Inactive
	6	-0.438	Active	-0.291	Uncertain
4	1	-0.345	Uncertain	-0.218	Uncertain
	2	-0.363	Active	-0.216	Uncertain
	3	-0.461	Active	-0.009	Inactive
	4	-0.389	Active	-0.338	Uncertain
	5	-0.534	Active	-0.524	Active
	6	-0.252	Uncertain	-0.330	Uncertain
5	1	-0.295	Uncertain	-0.395	Active
	2	-0.526	Active	-0.409	Active
	3	-0.407	Active	-0.305	Uncertain
	4	-0.269	Uncertain	-0.333	Uncertain
	5	-0.548	Active	-0.324	Uncertain
	6	-0.769	Active	-0.331	Uncertain
6	1	-0.408	Active	-0.503	Active
	2	-0.550	Active	-0.313	Uncertain
	3	-0.628	Active	-0.312	Uncertain
	4	-0.566	Active	-0.256	Uncertain
	5	-0.582	Active	-0.283	Uncertain
	6	-0.519	Active	-0.289	Uncertain
Average		-0.443	Active	-0.320	Uncertain
Std. Dev.		0.122	-	0.108	-

4.5 CHLORIDE CONCENTRATION TESTING

The chloride concentrations at 1-in. depth intervals together with the depths to reinforcement are shown in Tables 4.5 and 4.6, respectively, for each test location. Because chloride concentrations were only measured to a depth of 7 in. on decks without SIPMFs to avoid drilling through the bottom of the deck, the entries for chloride concentration at a depth of 8 in. are given as hyphens in Table 4.6. At a depth of 2 in., which was the cover thickness required by the UDOT specification in place at the time the decks were constructed, the average chloride concentration is 5.8 lbs of chloride per cubic yard of concrete, or 82 percent, higher in the decks with SIPMFs than the chloride concentration in those without SIPMFs. Table 4.7 provides a summary of the average chloride concentrations of all 12 decks at 1-in. intervals. On average, the chloride concentrations at each interval in decks with SIPMFs are 205 percent greater than the chloride concentrations measured at the same depths in decks without SIPMFs.

4.6 STATISTICAL ANALYSES

Statistical analyses were utilized to evaluate the significance of differences between properties measured on decks with SIPMFs and those measured on decks without SIPMFs. As part of the evaluation, the values of two uncontrolled variables, age and cover, were examined. Calculated from data provided in Tables 3.1 and 3.2, the average ages of decks with and without SIPMFs at the time of testing were 17 and 20 years, respectively, at the time of testing, suggesting that the decks with SIPMFs probably experienced fewer traffic loads, fewer freeze-thaw cycles, and less total salt application than the decks without SIPMFs by the time of testing. As shown in Tables 4.5 and 4.6, the concrete cover thicknesses for decks with and without SIPMFs were 2.29 and 2.62 in., respectively, indicating that the decks with SIPMFs had reduced protection from chlorides compared to decks without SIPMFs.

Given that only a limited number of bridge decks were available for the study, differences in age were expected; however, differences in concrete cover were not expected since the same cover specification was used for construction of all of the decks. While the inconsistency in cover thickness may reflect fundamental differences between

TABLE 4.5 Chloride Concentration Data for Decks with SIPMFs

Deck ID	Test Area	Chloride Conc. (lbs Cl ⁻ /yd ³ Concrete) at 1-in. Intervals								Cover (in.)
		1 in.	2 in.	3 in.	4 in.	5 in.	6 in.	7 in.	8 in.	
C-460	1	13.9	4.5	0.8	0.1	0.0	0.0	0.1	0.0	2.16
	2	21.5	12.4	5.2	2.1	0.7	0.0	0.0	0.0	1.75
	3	21.9	11.3	5.8	1.7	0.4	0.3	0.1	0.1	1.34
	4	24.9	16.3	7.9	5.0	3.2	2.0	1.7	0.0	1.65
	5	17.1	5.2	1.2	0.4	0.1	0.1	0.1	0.0	1.41
	6	26.2	10.1	3.1	0.6	0.1	0.1	0.1	0.0	1.91
C-688	1	15.5	5.5	2.5	0.2	0.1	0.1	0.1	0.0	2.58
	2	27.0	17.9	8.2	2.3	0.4	0.2	0.1	0.0	2.37
	3	15.5	9.4	5.1	2.9	1.4	0.5	0.3	0.0	2.59
	4	19.6	8.9	3.8	1.1	0.2	0.1	0.1	0.0	3.21
	5	14.9	10.5	8.6	5.3	2.4	0.9	0.4	0.0	3.39
	6	18.3	9.6	4.2	0.9	0.2	0.0	0.0	0.0	3.26
C-698	1	30.8	19.9	19.9	3.1	3.1	0.1	0.1	0.0	1.85
	2	27.9	15.5	6.9	2.4	0.5	0.1	0.1	0.0	2.06
	3	31.1	23.0	13.1	7.0	3.1	1.0	0.3	0.0	1.91
	4	27.4	15.7	7.3	2.9	0.6	0.2	0.0	0.0	1.93
	5	17.6	9.0	4.5	1.5	0.3	0.1	0.1	0.0	1.98
	6	24.2	10.0	5.9	3.2	1.0	0.4	0.1	0.0	2.42
C-699	1	14.6	4.2	3.0	0.6	0.2	0.1	0.1	0.0	1.73
	2	26.5	21.7	13.2	5.6	2.3	0.3	0.0	0.0	1.71
	3	22.4	14.6	6.9	3.2	0.8	0.1	0.0	0.0	2.48
	4	26.4	20.7	11.8	5.1	1.5	0.3	0.1	0.0	1.97
	5	18.3	10.1	5.1	2.8	0.5	0.1	0.1	0.0	2.82
	6	29.5	19.5	14.2	9.6	4.7	2.5	1.6	0.0	2.82
C-759	1	19.6	12.7	6.8	3.8	1.5	0.3	0.1	0.1	2.97
	2	13.4	9.6	5.7	2.9	0.9	0.1	0.0	0.0	3.13
	3	13.2	9.4	5.8	2.9	1.0	0.5	0.8	0.3	3.62
	4	11.2	8.6	5.1	2.3	0.4	0.2	0.1	0.1	2.85
	5	19.7	12.6	7.2	3.9	1.6	0.8	0.1	0.1	3.19
	6	14.7	9.3	5.9	3.2	1.4	0.4	0.1	0.0	2.34
C-760	1	35.4	21.2	12.7	5.9	2.3	0.6	0.2	0.0	1.99
	2	26.7	14.0	6.3	2.1	0.2	0.0	0.1	0.0	1.79
	3	30.7	18.2	9.9	5.2	1.8	0.7	0.3	0.0	1.79
	4	31.8	18.3	9.7	4.4	1.4	0.3	0.1	0.0	1.48
	5	20.4	14.4	7.7	4.0	2.0	0.9	0.4	0.0	2.11
	6	16.0	8.1	3.6	1.5	0.3	0.1	0.1	0.0	1.83
Average		21.9	12.8	6.9	3.0	1.1	0.4	0.2	0.1	2.29
Std. Dev.		6.4	5.2	4.0	2.1	1.1	0.5	0.4	0.1	0.62

TABLE 4.6 Chloride Concentration Data for Decks without SIPMFs

Deck ID	Test Area	Chloride Conc. (lbs Cl ⁻ /yd ³ Concrete) at 1-in. Intervals								Cover (in.)
		1 in.	2 in.	3 in.	4 in.	5 in.	6 in.	7 in.	8 in.	
F-500	1	6.9	0.2	0.1	0.1	0.1	0.0	0.0	-	2.67
	2	8.4	2.2	0.5	0.1	0.0	0.0	0.1	-	2.45
	3	13.8	0.2	0.0	0.0	0.0	0.0	0.0	-	2.49
	4	9.2	0.6	0.1	0.1	0.1	0.1	0.1	-	2.59
	5	9.9	2.1	0.3	0.1	0.1	0.0	0.1	-	2.33
	6	11.4	0.3	0.0	0.1	0.1	0.1	0.1	-	2.37
F-504	1	17.7	6.5	1.3	0.0	0.0	0.0	0.0	-	2.15
	2	21.1	13.1	5.1	1.4	0.2	0.0	0.0	-	2.43
	3	23.3	10.7	3.0	0.7	0.1	0.1	0.0	-	2.69
	4	14.4	5.8	2.7	0.7	0.1	0.1	0.1	-	2.88
	5	21.7	15.9	7.6	3.1	0.5	0.0	0.0	-	2.73
	6	16.1	7.4	3.1	1.0	0.1	0.1	0.0	-	2.31
F-506	1	9.6	1.9	0.1	0.0	0.0	0.0	0.0	-	2.27
	2	18.7	11.2	2.7	0.3	0.1	0.0	0.0	-	2.87
	3	24.0	10.6	1.5	0.2	0.1	0.0	0.1	-	2.70
	4	17.1	6.6	1.1	1.3	0.0	0.0	0.0	-	2.27
	5	22.7	13.0	0.0	0.1	0.1	0.1	0.1	-	3.08
	6	15.1	8.0	3.3	1.0	0.1	0.0	0.0	-	3.01
C-726	1	19.8	16.5	8.9	2.1	0.1	0.0	0.0	-	1.71
	2	18.7	13.2	7.2	2.4	0.6	0.1	0.0	-	1.81
	3	25.0	19.9	12.5	5.4	1.1	0.1	0.0	-	2.04
	4	20.6	14.5	4.3	0.8	0.5	0.1	0.1	-	2.41
	5	22.9	13.8	4.3	0.7	0.0	0.0	0.0	-	2.18
	6	16.7	9.5	5.3	1.7	0.2	0.0	0.0	-	2.02
C-736	1	14.2	5.7	0.6	0.1	0.1	0.3	0.7	-	2.74
	2	19.2	6.8	0.2	0.1	0.1	0.1	0.1	-	3.17
	3	20.4	6.0	0.6	0.2	0.1	0.1	0.1	-	2.95
	4	14.8	4.1	0.8	0.4	0.1	0.0	0.0	-	2.87
	5	13.8	4.1	0.1	0.1	0.0	0.0	0.0	-	3.19
	6	13.8	3.2	0.2	0.1	0.0	0.0	0.0	-	3.12
C-752	1	14.5	4.8	2.7	0.7	0.2	0.3	0.2	-	3.72
	2	18.9	3.4	0.2	0.2	0.2	0.2	0.1	-	3.48
	3	22.3	8.1	1.1	0.7	0.7	0.8	0.7	-	3.31
	4	13.9	0.8	0.3	0.2	0.2	0.2	0.1	-	2.23
	5	17.8	2.0	0.2	0.2	0.2	0.2	0.2	-	2.58
	6	8.6	0.3	0.2	0.2	0.2	0.1	0.1	-	2.39
Average		16.6	7.0	2.4	1.1	0.2	0.1	0.1	-	2.62
Std. Dev.		4.9	5.4	3.0	1.1	0.2	0.1	0.2	-	0.46

TABLE 4.7 Summary of Chloride Concentration Data

Depth (in.)	Chloride Concentration (lbs Cl/yd ³ Concrete)	
	With SIPMFs	Without SIPMFs
1	21.9	16.6
2	12.8	7.0
3	6.9	2.4
4	3.0	1.1
5	1.1	0.2
6	0.4	0.1
7	0.2	0.1
8	0.1	-

deck construction practices using conventional formwork and SIPMFs, it is probably due to coincidence only.

Because uncontrolled variability in each of these factors could potentially mask the influence of the SIPMFs on each of the response variables, an analysis of covariance (ANOCOVA) was utilized as a normalizing procedure to separate the effects of age, cover, and presence of SIPMFs on each of the deck properties. This approach avoided confounding the effects of the covariates, age and cover, with the effects of SIPMFs by adjusting the values of the measured deck properties, or response variables, for differences in the covariates between decks with and without SIPMFs.

Data obtained from decks with and without SIPMFs were treated as samples from two different populations, and the ANOCOVA was utilized to compare the population means associated with each response variable while controlling the probability of making a Type I error. A Type I error is committed upon rejection of a true null hypothesis in favor of a false alternative, where the null hypothesis is the postulation that the population means are equal and the alternative is the conjecture that the means are different. The probability of occurrence for a Type I error is denoted by the symbol α , which is selected by the researcher as the tolerable level of error for the given experiment. The value of α is compared to the level of significance, or p -value, computed from the sample data in the ANOCOVA, where the p -value represents the probability of observing a sample outcome more contradictory to the null hypothesis

than the observed sample result. When the p -value is less than or equal to α , the null hypothesis can be rejected, leading to acceptance of the alternative hypothesis.

However, when the p -value is greater than α , one must conclude that insufficient evidence exists to reject the null hypothesis. In this study, analyses were conducted using the standard α value of 0.05. At this α level, only a 5 percent chance exists for falsely claiming that the two types of decks were different.

The results of the statistical analyses presented in Table 4.8 include the average, standard deviation, and p -value for each of the measured properties. The p -values associated with age and cover were both less than 0.05 and therefore justify treatment of those factors as covariates in the ANOCOVA. Conversely, however, all but one of the p -values associated with distress measurements are greater than 0.05; therefore, among the distress measurements, only the crack width was determined to be significantly different between the two types of decks at the time of testing. No p -values for pothole size or pothole density are provided because the decks with SIPMFs had no potholes and therefore could not be evaluated in the ANOCOVA. The inability to identify significant differences between the two types of decks with regard to crack density, number of

TABLE 4.8 Results of Statistical Analyses

Property	With SIPMFs		Without SIPMFs		p -value
	Average	Std. Dev.	Average	Std. Dev.	
Age (yr)	17	1	20	2	< 0.0001
Cover (in.)	2.29	0.62	2.62	0.46	0.0120
Crack Width (in.)	0.018	0.007	0.025	0.015	0.0188
Crack Density (ft/yd ³)	2.58	1.36	3.22	2.26	0.2510
Number of Delaminations	0.33	0.67	0.17	0.45	0.9843
Delamination Size (ft ²)	0.89	0.16	1.25	0.56	0.5440
Delamination Density (ft ² /yd ²)	0.07	0.15	0.04	0.12	0.7851
Number of Potholes	0.00	0.00	0.06	0.23	0.3891
Pothole Size (ft ²)	-	-	1.50	0.71	-
Pothole Density (ft ² /yd ²)	-	-	0.02	0.09	-
Schmidt Rebound Number	39	2	35	5	0.0002
Half-Cell Potential (V)	-0.443	0.122	-0.320	0.108	0.0009
Chloride Concentration at 2-in. Depth (lbs Cl/yd ³ Concrete)	12.8	5.2	7.0	5.4	< 0.0001

delaminations, delamination size, delamination density, number of potholes, pothole size, and pothole density could suggest that, in fact, no differences existed, or it may be caused by insufficient statistical power resulting from comparatively high spatial variability associated with those parameters.

Table 4.8 further indicates that analyses of Schmidt rebound number, half-cell potential, and chloride concentration at 2-in. depth all yielded p -values less than 0.05, indicating that significant differences in these properties exist between decks with and without SIPMFs. Specifically, the decks with SIPMFs have a higher compressive strength, a more active state of corrosion, and a higher chloride concentration than the decks without SIPMFs.

In consideration of the collected data and information obtained from the literature, the author proposes that the observed differences in crack width, Schmidt rebound number, half-cell potential, and chloride concentration may all be explained by elevated moisture contents in the decks with SIPMFs compared to decks without SIPMFs. Higher concrete strength in the decks with SIPMFs may be attributable to an improved curing environment caused by the entrapment of moisture within the decks by the SIPMFs, and the higher strength would offer greater resistance to the formation of cracks and other distresses expected from corrosion of the reinforcing steel. Higher moisture contents in the bridge decks with SIPMFs might also retard the occurrence of drying shrinkage compared to decks without SIPMFs; excessive drying shrinkage would inevitably lead to more severe deck cracking. Increased moisture contents in decks with SIPMFs would also facilitate greater ionic current flow through the concrete and therefore sustain higher reinforcement corrosion rates. Finally, higher degrees of saturation would accelerate the diffusion of chlorides into the deck by providing greater continuity within the pore water system as mentioned earlier. Given these data, bridge engineers should understand that even though significant differences in the majority of distress measurements between decks with and without SIPMFs could not be identified in this study, decks with SIPMFs are clearly more susceptible to reinforcement corrosion than decks without SIPMFs and may therefore exhibit greater magnitudes of damage with time.

4.7 SUMMARY

The results of distress surveys, Schmidt hammer testing, half-cell potential testing, and chloride concentration testing were evaluated to investigate the effect of SIPMFs on the performance of concrete bridge decks. The distress survey results indicate that the average crack width and crack density for decks without SIPMFs were greater by 41 and 25 percent, respectively, than the corresponding values for decks with SIPMFs. Similarly, decks without SIPMFs had more potholes than decks with SIPMFs; in fact, the only deck that had potholes was a deck without SIPMFs. However, the delamination density for bridge decks with SIPMFs was 71 percent higher than that of decks without SIPMFs.

The average Schmidt rebound number for decks with SIPMFs was higher than that for decks without SIPMFs by an equivalent of 1,400 psi. The half-cell potential for decks with SIPMFs was 0.123 lower than that of decks without SIPMFs, indicating that a more active state of corrosion exists on decks with SIPMFs. On average, the chloride concentration in the bridge decks with SIPMFs was 205 percent greater than the concentration in the decks without SIPMFs.

ANCOVA testing was utilized to identify statistically significant differences in these properties between decks with and without SIPMFs. Age and cover were treated as covariates to avoid confounding their effects with the presence of SIPMFs. Among all of the distress measurements, crack width was the only parameter that was determined to be significantly different between the two types of decks at the time of testing. In addition, Schmidt rebound number, half-cell potential, and chloride concentration at 2-in. depth all yielded p -values less than 0.05, indicating that significant differences in these properties exist between decks with and without SIPMFs. Specifically, the decks with SIPMFs have a higher compressive strength, a more active state of corrosion, and a higher chloride concentration, which may all be attributable to elevated moisture contents in decks with SIPMFs arising from the reduction in deck surface area from which moisture may evaporate. These data indicate that decks with SIPMFs are clearly more susceptible to reinforcement corrosion compared to decks without SIPMFs and may therefore exhibit greater magnitudes of damage with time.

CHAPTER 5

CONCLUSION

5.1 SUMMARY

The objectives of this research were to investigate the effect of SIPMFs on concrete bridge decks in Utah. Six bridge decks with SIPMFs and six decks without SIPMFs were selected for testing by UDOT personnel. Because all 12 decks were located within the I-215 corridor in the vicinity of Salt Lake City, Utah, they were subject to similar traffic loading, climatic conditions, and maintenance treatments, including applications of deicing salts during winter months.

On each bridge deck, six randomly distributed 6-ft by 6-ft test locations were evaluated within the single lane closed for testing. Several tests were performed at each test location, including visual inspection, chain dragging, hammer sounding, Schmidt hammer testing, half-cell potential testing, and chloride concentration testing. The primary purpose of visual inspection was to document the presence of any cracks or potholes within each test location, and chain dragging and hammer sounding were performed to locate subsurface delaminations within each test location. From the deck distress surveys, the average crack width, crack density, number of potholes, pothole size, pothole density, number of delaminations, delamination size, and delamination density were calculated for each deck. Schmidt hammer testing was utilized in this study to estimate concrete strength, and half-cell potential testing and chloride concentration testing were included to evaluate the corrosion activity of the reinforcing steel. Because differences in deck age and average cover for the two deck types were found to be statistically significant, the collected data were subjected to ANOCOVA testing, with age and cover as covariates. All calculated p -values were compared to the standard value of 0.05.

5.2 FINDINGS

The distress survey results indicate that the average crack width and crack density for decks without SIPMFs were greater by 41 and 25 percent, respectively, than the corresponding values for decks with SIPMFs. Similarly, decks without SIPMFs had more potholes than decks with SIPMFs. However, the delamination density for bridge decks with SIPMFs was 71 percent higher than that of decks without SIPMFs.

The average Schmidt rebound number for decks with SIPMFs was higher than that for decks without SIPMFs by an equivalent of 1,400 psi. The half-cell potential for decks with SIPMFs was 0.123 lower than that of decks without SIPMFs, indicating that a more active state of corrosion exists on decks with SIPMFs. On average, the chloride concentration in the bridge decks with SIPMFs was 205 percent greater than the concentration in the decks without SIPMFs.

Among all of the distress measurements evaluated in the ANOCOVA, crack width was the only parameter that was determined to be significantly different between the two types of decks at the time of testing. In addition, Schmidt rebound number, half-cell potential, and chloride concentration at 2-in. depth all yielded *p*-values less than 0.05, indicating that significant differences in these properties exist between decks with and without SIPMFs. Specifically, the decks with SIPMFs have a higher compressive strength, a more active state of corrosion, and a higher chloride concentration, which may all be attributable to elevated moisture contents in decks with SIPMFs arising from the reduction in deck surface area from which moisture may evaporate. These data indicate that decks with SIPMFs are clearly more susceptible to reinforcement corrosion compared to decks without SIPMFs and may therefore exhibit greater magnitudes of damage with time.

5.3 RECOMMENDATIONS

Given these research findings, engineers should carefully compare the short-term advantages against the potential long-term disadvantages associated with the use of SIPMFs for concrete bridge deck construction. If SIPMFs are approved for use, engineers may consider applying surface treatments to the affected decks early in the

deck life to minimize the ingress of chlorides into the concrete over time and therefore retard the onset of reinforcement corrosion (21).

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